CALIFORNIA ENERGY COMMISSION

PROJECTED AUTOMOTIVE FUEL CELL USE IN CALIFORNIA

CONSULTANT REPORT

OCTOBER 2001
P600-01-022F

Gray Davis, *Governor*

CALIFORNIA ENERGY COMMISSION

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October 2001

1. Introduction

Fuel cell vehicles hold the promise of high efficiency and zero or near-zero emissions. While it will take many years if not decades for fuel cell vehicles to be mainstream, high-efficiency fuel cells have the potential to deliver comparable power, range and performance to today's conventional vehicles. High costs will remain the biggest challenge to automakers before commercial viability can be achieved.

This summary uses a Delphi method of opinions from experts to project technology, cost, and performance of fuel cell vehicles during the next 30 years. While much of the information is speculative due to the adolescent nature of this technology, it does give an idea of what is to come in the near and mid-term.

2. Fuel Cell Technologies

A fuel cell is similar to a battery in that electrochemical energy is used to produce electrical energy. Like batteries, multiple fuel cells can be stacked in series to increase the voltage of the system. However, unlike a battery, fuel cells never need to be recharged; instead, they utilize hydrogen fuel from an external tank and oxygen from air to derive power. Thus, fuel cells are essentially engines that combine the best attributes of both batteries (electrochemical energy conversion) and internal combustion engines (rapid refueling via an external fuel supply).

The fundamental power-producing unit of a basic hydrogen fuel cell is the membrane-electrode assembly (MEA) consisting of a cathode, an anode, and an electrolyte. Oxygen (usually from ambient air) enters through the cathode while hydrogen enters through the anode. Usually in the presence of a catalyst on the membrane, the hydrogen molecules split into protons and electrons, with the protons passing through the electrolyte and the electrons passing through an external circuit. At the cathode side, water and electricity are produced, resulting in electrical current that can be used as a power source.

Fuel cell stack conversion efficiency is from 45 to 70 percent compared to the 30 to 40 percent typical of internal combustion (IC) engines. Each hydrogen fuel cell – consisting of a single MEA and a bipolar plate – generates around 0.6 to 0.8 volts. Single cells are combined end-to-end into a fuel cell stack to produce the desired level of electrical power. Fuel cells tend to have high efficiency at low loads while IC engines typically have high efficiency at high loads. Another key advantage of fuel cells is that they provide zero emissions in the case of direct-hydrogen systems, and near-zero emissions in the case of systems that use on-board reformers (discussed further below).

There are several types of fuel cells, distinguished mostly by the chemistry, electrolyte, and fuel feedstock. These are shown in Table 1. Of these, two show the most promise

Table 1. Characteristics of Fuel Cell Types

Fuel Cell Type	Proton Exchange Membrane	Alkaline	Phosphoric Acid	Molten Carbonate	Tubular Solid Oxide	Planar Solid Oxide
Operating Temperature	70-80°C	80-100°C	200-220°C	600-650°C	800-1000°C	500-800°C
Current Density	High	High	Moderate	Moderate	Moderate	High
Stage of Development	System prototypes	Space applications	Early commercial applications	Field demonstrations	Field demonstrations	Laboratory demonstrations
Likely Applications	Distributed generation, portable power and transportation	Space	Industrial, commercial	Electric utility, industrial, commercial	Electric utility, industrial, commercial	Distributed generation, APU
Advantages	Low temperature, quick start-up, solid electrolyte	High performance	High efficiency for co-generation, can use less hydrogen fuel	High efficiency, flexibility of fuels, accommodates carbon monoxide	High efficiency, flexibility of fuels, solid electrolyte, accommodates carbon monoxide	High efficiency, flexibility of fuels, solid electrolyte, accommodates carbon monoxide
Disadvantages	High sensitivity to fuel impurities, needs carbon monoxide removed from fuel supply	Needs carbon dioxide, CO, Sulfur removed from fuel and air supplies	Low current and power, large size and weight	High temperature causes corrosion & breakdown of cell components	Ceramic structure stability, sealing problem during termperature cycling	Ceramic structure stability, sealing problem during termperature cycling
Prospect for High Efficiency	Acceptible	Poor	Good	Excellent	Excellent	Excellent
Prospect for Low Cost	Good	Fair	Fair	Fair	Fair-Good	Good

Sources: NAVC, "Future Wheels," November 2000; Arthur D. Little Analysis.

for automotive applications, namely the Proton Exchange Membrane[1] Fuel Cell (PEMFC) and the planar Solid Oxide Fuel Cell (SOFC), which are discussed below.

2.1 Proton Exchange Membrane

The proton exchange membrane fuel cell (PEMFC) is favored for automobile propulsion because it has a relatively high power density, operates at low temperatures (see Table 1), permits adjustable power output, and can be started relatively rapidly. These positive attributes outweigh its disadvantages (compared with other fuel cells) of lower efficiency levels and its low tolerance for carbon monoxide contamination. Almost all fuel cell demonstration vehicles currently under development by the world's major automotive manufacturers use PEMFC stacks.

PEMFCs use hydrogen as a fuel, which can be stored as pure hydrogen on-board or produced on-board from other fuels using a fuel processor or reformer.

[1] Also know as a Polymer Electrolyte Membrane fuel cell.

A special type of PEMFC is the Direct Methanol-Air Fuel Cell (DMFC), which utilizes methanol, combined with water, directly as a fuel and ambient air for oxygen. This could be a less expensive, more convenient technology because it enables use of a liquid fuel without the need for an on-board reformer, while still providing a zero-emissions system. However, current research has demonstrated power density lower than other PEMFCs, significant research effort will be required to improve this.

2.2 Solid Oxide Fuel Cells

Planar Solid Oxide Fuel Cells (SOFCs) operate at relatively high temperatures (500 to 800°C), can use carbon monoxide (CO) and hydrogen (H_2) fuel, have a good tolerance to fuel impurities, and use ceramic as an electrolyte. Transportation applications of this type of fuel cell will be limited to heavy-duty vehicle propulsion or auxillary power unit (APU) service due to its size and warm-up requirements. BMW is currently developing an APU using an SOFC with Delphi and Global Thermoelectric. Although SOFCs may eventually accept fuels directly, currently use of gasoline requires a simple reformer.

2.3 Reformers

As discussed in the next chapter, hydrogen storage on-board a vehicle is one of the largest technical problems to overcome with direct hydrogen PEMFC vehicles. On-board reformation of a hydrocarbon fuel into hydrogen allows the use of more established infrastructure, but adds additional weight and cost, reduces vehicle efficiency, and creates some emissions.

Reformers are high temperature devices that convert hydrocarbon fuels to CO and H_2. SOFCs can use this mixture directly, PEMFCs must combined these gases with steam to produce additional H_2 and convert the CO to carbon dioxide (CO_2). The CO_2 is then released to the atmosphere. On-board reformers are currently being developed by several companies. Reformer technologies include steam reforming, partial oxidation, and autothermal reforming. Fuel reformer development activities are shown in Table 2.

2.3.1 Steam Reforming

Steam reforming (SR) uses a catalyst to convert fuel and steam to hydrogen, carbon monoxide and carbon dioxide. The carbon monoxide is further reformed with steam to form more hydrogen and carbon dioxide. A purification step then removes carbon monoxide, carbon dioxide, and any impurities to achieve a high hydrogen purity level (97 to 99.9 percent). SR of methanol is the most developed and least expensive method for producing hydrogen from a hydrocarbon fuel on a vehicle, resulting in a 45 to 70 percent conversion efficiency that is limited by the endothermic nature of the reactions.

2.3.2 Partial Oxidation

Partial oxidation (POX) reforming is similar to SR in combining fuel and steam, but this process adds oxygen in an additional step, making the reaction exothermic. The process is less efficient than SR, but the exothermic nature of the reaction makes it more responsive than SR to variable load, an important feature of on-board reforming. Heavier hydrocarbons can be used in POX, but they have lower carbon-to-hydrogen ratios, which limit hydrogen production. This process is more expensive than SR. POX reformers are not widely used due to their lower efficiencies.

Table 2. Automotive Fuel Reformer Development Activities

Organization	Technology	Fuel(s)	Scale (power)
Delphi, GM, Opel	Low Temperature SR	Methanol	On-vehicle (50 kW)
Fuji	Low Temperature SR	Methanol	On-vehicle (57 kW)
Ballard	Low Temperature SR	Methanol	Transit bus (100 kW) Submarine power generator
Catalytica	Autothermal reforming	Gasoline	R&D for on-vehicle (50 kW)
H2 Fuel/LLC/ANL	Autothermal reforming	Gasoline, Natural Gas, Ethanol	Prototype (3 kW), various applications
International Fuel Cells	High Temperature SR	Natural Gas, LPG, Methanol	PC25 fuel cell (200 kW) Transit bus (100kW)
Halder Topsöe, Siemens, KFA	Low Temperature SR	Methanol	Laboratory burner reformer Laboratory membrane Joule II, On-vehicle (30kW)
Argonne National Lab	Catalytic Partial Oxidation	Methanol, Ethanol, Gasoline, Natural Gas	10 kW
Nuvera	Autothermal reforming	Ethanol, Gasoline, JP-8	various applications 50 kW
General Motors, ExxonMobil	Autothermal reforming	Natural Gas, Methane, Gasoline	Stationary demo (5 kW) and small on-vehicle demo (25 kW battery charger) for Chevy S-10 Pickup
Shell	Catalytic partial oxidation (CPO)	gasoline	50 kW compact design for mobile and stationary use
McDermott Technology	Autothermal reforming	JP-8, gasoline	500 kW for marine use and 50 kW multifuel processor for vehicles
Hydrogen Burner Technology	Partial oxidation Autothermal reforming	Natural Gas, LPG, Methanol, Gasoline, Diesel	POX Industrial hydrogen production (50 kW, 300 kW) Prototype for vehicle (50 kW)
Johnson Matthey	Hot Spot™ partial oxidation	Methanol	Designed for industrial hydrogen and vehicles (10 kW) – able to be clustered

Sources: Unnasch, "Evaluation of Fuel Cell Reformer Emissions," 1999, company literature.

2.3.3 Autothermal Reforming

Autothermal reforming (ATR) combines both SR and POX so that the heat production from POX offsets the heat needs of SR. ATR produces a better concentration of hydrogen than POX but less than SR. ATR offers good response to variable loads and a good efficiency rate. The efficiency of an ATR depends upon the heat transfer between the burner and reformer.

3. Fuel Choices

A fundamental problem with fuel cell technology whether to store hydrogen or convert it from other fuels on-board the vehicle. All four principal fuels that automakers are considering – hydrogen, methanol, ethanol, and gasoline – pose serious challenges.

While direct hydrogen is the approach most favored because of its higher efficiency and zero emissions, it has significant storage problems. On the other hand, methanol, ethanol, and gasoline offer the advantages of liquid fuels, but require on-board reformers to convert the fuel to hydrogen. A discussion of each fuel option follows.

3.1 Direct Hydrogen

Approximately 40 million tons of hydrogen gas are produced annually on a global scale, but very little of this is used as an energy source. Most of the hydrogen produced is used in oil refining, and methanol and ammonia production. Most U.S. companies produce their own hydrogen through steam reformation of natural gas and consume it on-site. Only 5 percent of hydrogen production is sold to other facilities.

Hydrogen is colorless and odorless, thus hydrogen refueling stations will need leak detection devices to alarm personnel. With its low ignition temperature and wide flammability range, hydrogen poses unique fire hazards. In properly ventilated areas, however, hydrogen dissipates quickly, reducing this risk.

A vehicle hydrogen fueling station at the Chicago Transit Authority used liquid hydrogen delivered by truck from an industrial plant 300 miles away. During refueling, the hydrogen was pumped out and pressurized into compressed hydrogen storage tanks on the bus roof. This station was recently dismantled. Ford Motor Company has a similar station in Dearborn, Michigan. The California Fuel Cell Partnership also has a liquid to compressed hydrogen 16 vehicle fueling station in West Sacramento and is adding fueling for liquid hydrogen vehicles in late 2001.

Coast Mountain Transit (formerly British Columbia Transit) in Vancouver, Canada and SunLine Transit Agency in Palm Springs, California utilize on-site electrolysis (splitting of water into hydrogen and oxygen) to supply hydrogen to their fuel cell vehicles. Fleet-sized (1 to 200 vehicles) electrolysers are commercially available with residential-sized electrolysers expected to be available in 2004. Power for electrolysers is usually provided from renewable energy sources such as hydroelectric (Coast Mountain Transit) or photovoltaic arrays (SunLine Transit). SunLine Transit also has a 4200 scf per hour POX reformer system using natural gas as a feedstock and a Stuart Energy Systems electrolyser. In the summer of 2001, Honda developed a fueling station using solar photovoltaic arrays for electrolyzing hydrogen in Torrance, California.

The ability to use hydrogen directly in a fuel cell provides the highest efficiency and zero tailpipe emissions. However, hydrogen has a low energy density and boiling point, thus on-board storage tends to be large and heavy. There are three types of hydrogen storage under development: compressed hydrogen, liquefied hydrogen, and binding hydrogenate to solids in metal hydrides or carbon compounds. Table 3 compares on-board hydrogen storage methods to an vehicle range-equivalent amount of gasoline. Each is described in the following subsections.

Table 3. On-Board Hydrogen Storage Options

Fuel	Gasoline	Compressed Hydrogen	Liquefied Hydrogen	Metal Hydrides
Energy (MJ)	1,408	664	664	664
Fuel Weight (kg)	29.5	4.7	4.7	4.7
Tank Weight (kg)	13.4	63.3 – 86	18.6	120
Total Fuel System Weight (kg)	43.2	67.9 – 90.5	23.3	125
Volume (liters)	40.1	409 – 227	178	120
Vehicle Range (km)	600	600	600	570
Development Status	Commercial	Commercial Prototype	Initial Prototype	Initial Prototype

Source: NAVC, "Future Wheels," November 2000.

3.1.1 Compressed Hydrogen

Compressed hydrogen offers the least expensive method for on-board storage of hydrogen. However, at normal CNG operating pressures of 24 MPa (3500 psi), reasonably-sized commercially-available pressure vessels will provide limited range for a fuel cell car (about 190 km or 120 mi). Pressure vessels capable of 34 MPa (5000 psi) are now being used by DaimlerChrysler and Hyundai. Quantum is conducting research of high performance hydrogen storage systems, looking at pressure vessels capable of up to 69 MPa (10000 psi), which would permit a 645 km (400 mi) driving range with a total vessel mass less than 68 kg (150 lb). However, the real problem is size -- unlike heavy-duty vehicles such as transit buses -- automobiles offer relatively small platforms to accommodate multiple pressure vessels.

3.1.2 Liquefied Hydrogen

Liquefied hydrogen does not have the high storage size and weight penalty as compressed hydrogen, but it is still bulkier than gasoline storage. Hydrogen's low boiling point requires excellent insulation of storage containers, similar to the way in which liquefied natural gas is currently stored on heavy-duty vehicles. Maintaining the extreme cold temperature (-253°C) during refueling and on-board storage currently poses a great technical challenge. Under worst case conditions, 25 percent of liquid hydrogen can be boiled off during refueling and about 1 percent is lost per day in on-board storage. Systems using liquefied hydrogen have been developed by DaimlerChrysler and others.

3.1.3 Hydrides

Another option for hydrogen storage is to use materials that absorb hydrogen into their crystal structure (metal hydrides). Hydrogen bonds to more than 80 metallic compounds forming a weak attraction that stores hydrogen until heated. Metal hydride systems can be categorized as either low temperature (<150°C) or high (300°C). Since heat is required to release the hydrogen, hydride systems avoid safety concerns surrounding compressed or liquefied hydrogen. However, the metal compounds used to attract hydrogen tend to be very heavy resulting in only 1.0 to 1.5 percent hydrogen by weight.

Energy Conversion Devices (ECD) is working on a proprietary magnesium alloy that can store 7.0 percent hydrogen by weight.

3.1.4 Other Storage Options

Carbon nanotubes – microscopic carbon tubes synthesized in the laboratory – can be used to absorb hydrogen. Despite early claims, research results have been questionable and it is not clear that they would offer practical advantages.

Glass microspheres are small, hollow glass spheres (0.03 to 0.05 mm in diameter) that allow hydrogen to enter when heated to 200°C to 400°C. The hydrogen becomes trapped once the temperature cools, but is released again upon heating. This technology is still in the development stage, and its performance implications from a system perspective are not clear at this time.

3.2 Methanol

Several automakers are using methanol to power fuel cells. Some believe that methanol fuel cells could bridge the gap while a hydrogen distribution infrastructure is being built over the next decade or two. U.S. production of methanol is currently 2.6 million gallons per year at the 18 methanol production plants which meets approximately 75 percent of U.S. methanol demand. The rest is imported from Canada and to a lesser extent Latin America. Considerable natural gas reserves have been found in Alaska, Southwestern U.S. and Canada, which could be a significant supply of a relatively cheap feedstock. If 10 percent of offshore flare gas was captured and converted to methanol, it would supply 9.5 million fuel cell vehicles annually.

The major current market for methanol in automotive fuel applications is its use as a feedstock for the gasoline additive methyl tertiary butyl ether (MTBE). With MTBE being phased out in California as a gasoline oxygenate after 2002 due to environmental concerns, significant quantities of methanol could be available for vehicle use.

Fuel providers and automakers have shown concern about methanol toxicity, which can result in blindness or death if ingested. It can also enter the body through contact with the skin. Spills, however, are less of a concern because methanol diffuses rapidly in water and air with no long term effects. Some indicate that a taste deterrent should be used to prevent accidental ingestion of methanol.

There are very few existing methanol refueling stations, with most concentrated in California. Of these most are M85 stations, a mixture of 85 percent methanol and 15 percent gasoline. DMFCs and SR Fuel cells require 100% methanol. While present M85 stations could be converted to M100, the cost of converting a gasoline station to M100 is estimated at approximately $60,000.

3.3 Ethanol

Ethanol is a renewable resource and has been targeted as a potential candidate for replacing MTBE in gasoline. Over 1.4 billion gallons of ethanol were produced in 1998 from 55 facilities in the U.S. Over 88 percent of these facilities are in the Midwest. If ethanol is used as a replacement for MTBE, the Energy Information Administration (EIA) predicts that 2.7 billion gallons of ethanol will be consumed in 2020.

Ethanol is considered less toxic than either gasoline or methanol. There are currently 76 E85 fueling stations in the U.S., most of which are in the Midwest. Ethanol reformers are similar to gasoline reformers but offer higher efficiency and slightly lower technical risk. They could use E100, E95, or E85.

3.4 Gasoline

Using reformers for on-board extraction of hydrogen from gasoline is one approach to commercialization of fuel cell vehicles, since the gasoline infrastructure is already in place. However, producing hydrogen from gasoline in a vehicle system is much more difficult than from methanol. The reformation reactions occur at 850°C to 1000°C, making the devices slow to start and the chemistry temperamental. The size of the reformer is also an issue[2], making it difficult to fit under the hood of a standard sized vehicle. Furthermore, there is concern about the sulfur levels in current gasoline and carbon monoxide in the reformer effluent poisoning the fuel cell.

In general, fuel-reforming technology requires complex integration of all the components into a compact, lightweight, efficient, and low-cost system. The key is to couple the various systems together, some of which generate heat and others use heat, to carefully optimize the heat and energy economics. On-board reforming systems currently suffer from packaging issues, extra weight, complicated controls, and high cost.

4. Fuel Cell Vehicle Design Challenges

While vehicle cost is probably the biggest design challenge that automakers face with fuel cell vehicles, several technical design challenges still exist before fuel cell vehicles are practical. These include higher temperature operation, better powertrain density, water management, precious metals content, compatibility with environmental conditions, start-up time, and system life.

4.1 High Temperature Electrolytes

One of the most important improvements in PEMFCs is the development of high-temperature electrolytes that could operate at temperatures in excess of 100°C, more or less independently of the level of humidification. The implications include:

- *Improved CO tolerance*, reducing or obviating the need for a preferential oxidation reactor and for air-bleed (thus improving system efficiency by 5–10%) and considerably reducing start-up time. The remaining CO will be combusted in the catalytic tailgas burner to prevent emissions of CO.

- *Facilitated Stack Cooling*, reducing considerably the radiator area and the stack cooling plate requirements and consequently reducing system weight considerably

[2] The slow starting, tempermental chemistry and large size and costs apply to all reformers, though perhaps a little less to methanol reformers.

because greater driving temperature differences will be available for each of these systems.

- *Humidity-Independent Operation,* which will be necessary to allow the use of high temperature membranes, reducing the need for humidifiers and water recovery, again reducing weight and cost and making FCV operation consistent with typical automotive environmental conditions.

4.2 Powertrain Density

Powertrain power density has been considerably improved since the early 1990s but requires significant additional improvement for vehicle integration. Generally, increased power density tends to almost proportionally reduce system cost, so improving power density is doubly important because of the continuing need for cost reduction. Specifically:

- Fuel cell stack power densities over 1 kW/l have been demonstrated, but further improvements, especially under high-efficiency operation, are necessary.

- The weight and volume associated with thermal and humidity management in the fuel cell subsystem is currently unacceptably high. The development of high-temperature, humidity-independent membrane and stack technology would address this issue.

- Additional increases in fuel processor power density, mainly through improved catalyst space velocities, will be required to achieve acceptable system power density. In addition, a simplification of the system is important. The development of high-temperature membranes would significantly simplify or allow the elimination of the CO polishing step before the stack (the so-called preferential oxidation reactor), leading to considerable weight and cost savings.

- Although the weight of compressed hydrogen storage systems is approaching acceptable levels, their volume is still too large. A breakthrough in hydride storage or other storage methods could help, but no material with clearly winning characteristics appears to have been publicly described.

4.3 Water Management

Simplification of stack water management is a key hurdle to further improvements in stack power density and stack performance. Development of high-temperature membranes would remove the difficulties of handling liquid water in the stack and the necessity of recovering and recycling large amounts of water from the stack effluents.

4.4 Precious Metals Content

Additional reductions in precious metal use for FCVs will be required to achieve transportation market cost competitiveness. Currently, the overall platinum content of a fuel cell powertrain is around 4 g/kW, which, at current prices, represents a cost of $60/kW. Based on fundamental electrocatalysis experiments and analysis, there are certain limits to the reduction of the platinum content. Nevertheless, a further reduction by a factor of 5 to 10 appears both possible and necessary to allow fuel cell technology to approach competitive costs, compared with alternative advanced powertrains.

4.5 Compatibility with Environmental Conditions

Compatibility of the fuel cell system with vehicle environmental conditions is needed to enable vehicle operation under everyday conditions. Specifically:

- Tolerance of the fuel cell system to air-borne sulfur, ammonia, and heavy hydrocarbons must be improved. Most likely, reliable traps will be needed to address most of these sensitivities.

- Although stack tolerance of freezing conditions has been improved, incompatibility with high ambient temperatures and low humidity still limits the operating conditions for fuel cells. The introduction of high-temperature membranes would largely solve this problem.

4.6 Start-Up Time

System start-up time of reformer-based fuel cell power units must be improved to allow practical operation of fuel cell powertrains and to achieve better system efficiency. As alluded to above, this requires a combination of:

- increased power density, reducing the amount of material to be heated up,

- widening of the temperature windows of operation for each of the system components, and

- improved automatic system and temperature controls.

4.7 System Life

Component life, in particular stack life, must be improved to achieve acceptable system life. Most of the concerns about component life involve:

- membrane stability and life,

- catalyst deterioration (leading to a loss of operating cell voltage and hence system efficiency), and

- delamination of the membrane electrode assembly.

Although increasing catalyst loadings can compensate for the second issue, this does not constitute an acceptable solution, because it would increase cost. Despite the many very tough challenges, fundamental technology limits do not appear to present absolute barriers for fuel cell application to powertrains.

5. Present Prototype Vehicles

Several manufacturers have built prototype fuel cell vehicles. Most claim fuel cell vehicles will be available for purchase before the end of the decade, several in the next few years in a limited market. While some details are not available, Table 4 provides vehicle characteristics for the current concept vehicles produced by the manufacturers. Each manufacturer’s vehicles are described in the subsections to follow.

Fuel cells will most likely be incorporated into conventional vehicle bodies, modified to fit the fuel cell and electric drivetrain. As noted below, fuel cell vehicles most likely will have reduced top speeds and acceleration rates in comparison to IC engine vehicles to reduce vehicle costs. In addition, it is likely that they will be heavier and have reduced truck storage space.

To aid in the commercialization of fuel cell vehicles, the California Fuel Cell Partnership was formed. The California Fuel Cell Partnership is a voluntary alliance of automakers, fuel cell producers, and energy companies, as well as state and federal government organizations, working to demonstrate and promote awareness of fuel cell vehicle technology. This joint project is aimed at demonstrating the everyday practicality of fuel cell vehicles and preparing the California market for this new technology. The partnership plans to test more than 70 cars and buses between 2001 and 2003, incorporating innovative drive technologies under everyday operating conditions fueled by hydrogen, methanol, and a pure form of gasoline.

5.1 DaimlerChrysler

DaimlerChrysler recently introduced two new prototype fuel cell vehicles, the NECAR 5, which is based upon the Mercedes A-Class and the Commander 2 SUV which is based upon the Jeep Cherokee. Both cars generate hydrogen on-board by reforming methanol. DaimlerChrysler is predicting that it will introduce the first fuel cell passenger cars in 2004. The NECAR 5 uses a Ballard Mark 900 fuel cell unit and methanol reformer. The Jeep Commander 2 uses two Ballard Mark 700 fuel cells with a methanol reformer. It also contains a 90 kW nickel metal hydride battery to provide power assist during acceleration and towing heavy payloads. It gets 24 mpg (gasoline equivalent) in combined driving cycle tests, compared to 18 mpg average for the standard Cherokee. The Commander 2 weighs 2590 kg, slightly more than typical full-sized SUVs. The 1150 kg increase over the standard Cherokee includes the hybrid-electric fuel cell powertrain, which weights approximately 500 kg more than the standard IC engine.

In addition, DaimlerChrysler has developed the NECAR 4A, a California version that operates on compressed hydrogen. It uses a Ballard Mark 900 fuel cell and three tanks of hydrogen at 35 MPa. This gives the vehicle a range of 190 km.

DaimlerChrysler is also working with XCELLSiS to develop a gasoline reformer for on-board production of hydrogen. The prototype 50-kW multi-fuel system with compact design for mobile applications has been designed and tested during an 18 month research project.

Table 4. Current Concept Light-Duty Fuel Cell Vehicles

Features	DaimlerChysler	DaimlerChysler	General Motors
Vehicle	NECAR 4A	NECAR 5	HydroGen1
Platform	A-Class	A-Class	Opel Zafira
Body Style	4 Door	4-Door	Van
Overall Length	3.57 m	3.57 m	4.32 m
Overall Width	1.72 m	1.72 m	2.00 m
Wheelbase	2.42 m	2.42 m	2.69 m
Curb Weight	1750 kg	1430 kg	1570 kg
Fuel	Compressed H_2	Methanol	Liquid H_2
Fuel Pressure	35 MPa	--	--
Range	190 km	480 km	400 km
Top Speed	145 km/h	150 km/h	135 km/h
Fuel Cell	Ballard Mark 900	Ballard Mark 900	GM 60 kW PEMFC
Electric Motor	55 kW	55 kW	56 kW

Features	Ford	Volkswagen	Honda
Vehicle	Focus FCV	Bora Hymotion	FCX-V3
Platform	Ford Focus	Volkswagen Jetta	EV Plus
Body Style	4 Door Sedan	4 Door Sedan	2 door
Overall Length	4.34 m	4.38 m	4.05 m
Overall Width	1.76 m	1.73 m	1.78 m
Wheelbase	2.62 m	2.51 m	2.53 m
Curb Weight	1727 kg	N/A	1750 kg
Fuel	Compressed H_2	Liquid H_2	Compressed H_2
Fuel Pressure	24 MPa	--	25 MPa
Range	160 km	355 km	180 km
Top Speed	128 km/h	145 km/h	130 km/h
Fuel Cell	Ballard Mark 900	Ballard Mark 900	62 kW Ballard PEMFC
Electric Motor	67 kW	75 kW	60 kW

Features	Toyota	Hyundai	Nissan
Vehicle	FCHV-4	Santa Fe FCV	Xterra FCV
Platform	Highlander	Hyundai Santa Fe	Nissan Xterra
Body Style	SUV	SUV	SUV
Overall Length	4.68 m	4.50 m	4.52 m
Overall Width	1.83 m	1.84 m	1.79 m
Wheelbase	2.72 m	2.62 m	2.65 m
Curb Weight	N/A	1615 kg	N/A
Fuel	Compressed H_2	Compressed H_2	Compressed H_2
Fuel Pressure	25 MPa	35 MPa	25 MPa
Range	250 km	200 km	
Top Speed	150 km/h	128 km/h	120 km/h
Fuel Cell	90 kW PEMFC	IFC S300	Ballard Mark 900
Electric Motor	80 kW	65 kW	N/A

Sources: AEI, “Fuel Cells Start to Look Real,” March 2001, automobile company literature.

5.2 General Motors

General Motors HydroGen1 is a five-seat concept vehicle powered by a 56 kW electric motor and a 60 kW PEMFC that runs on liquid hydrogen. The HydroGen1, based upon the Opel Zafira, has a curb weight of 1570 kg, 150 kg heavier than the standard Zafira. The fuel cell system generates between 125 and 200 V depending upon load conditions. The car has a top speed of 135 km/h and a range of about 400 km. GM claims that the vehicle will accelerate from 0 to 97 km in less than 16 seconds, about 2.5 seconds slower than the standard Opel Zafira.

One of the largest breakthroughs is being able to start the fuel cell at low temperatures. The HydroGen1 can achieve full power in 30 seconds from -20°C and in 60 seconds from -30°C.

GM and ExxonMobil are working on a gasoline reformer technology that could have an 80 percent conversion efficiency, resulting in a fuel cell vehicle that was 40 percent efficient, almost double that of a current IC engine vehicle. GM indicates that their first commercial fuel cell vehicle, a joint venture with Toyota, is targeted for 2003.

5.3 Ford Motor Company

The Ford Focus FCV is targeted to be commercially available in 2004. It has a range of about 160 km on compressed hydrogen and power comparable to the standard Focus. Ford indicates that the cost of the fuel cell is the biggest technical challenge, one that they feel they won't likely solve before 2010.

The Focus FCV uses a Ballard 900 fuel cell stack, which features an 80-kW power output. It has a curb weight of 1727 kg, over 560 kg heavier than the standard Focus.

5.4 Volkswagen

The Volkswagen Bora HyMotion has a storage capacity of 49 liters of liquid hydrogen giving it a range of about 355 km. It has an asynchronous electric motor with a power output of 75 kW and a 0 to 97 km acceleration time of 12.5 seconds, about 1.7 seconds slower than the standard Jetta (the U.S. equivalent of the European Bora). The Bora HyMotion can reach a top speed of 145 km/h and stores 50 liters of liquid hydrogen, which results in a vehicle range of about 350 km.

5.5 Honda

Honda's FCX-V3 is specially made on the EV Plus platform with an ultracapacitor to provide peak power and accept energy from regenerative braking. It uses a Ballard 62 kW fuel cell together with a 60 kW synchronous electric motor. Honda claims this hybrid design gives an overall vehicle efficiency of 40 percent. Compressed hydrogen at 25 MPa is stored in its 98 liter carbon-fiber-wrapped pressure cylinder giving it an 180 km range. Top speed is 130 km/h. Honda plans to reduce mass by 5 to 10 percent, decrease cost by 30% per year, and increase its range to 200 km by its 2003 release date.

5.6 Toyota

Toyota's FCHV-4 is based upon Toyota's Klyuger V (Highlander) SUV. It uses hydrogen stored in high pressure tanks and a TMC fuel-cell stack with an output of 90 kW. It also has a nickel metal hydride battery to allow regenerative braking. Toyota is currently testing 5 FCHV-4s in Japan and plans to provide 2 more cars to the California Fuel Cell Partnership.

5.7 Hyundai

Hyundai is using IFC's fuel cell in their Santa Fe FCEV SUV. The 75 kW fuel cell system uses compressed hydrogen at 35 MPa giving it a 200 km range. Its curb weight of 1615 kg is only 50 kg heavier than the standard Santa Fe.

5.8 Nissan

The Nissan Xterra FCV is an SUV which uses a Ballard Mark 900 fuel cell and pressurized hydrogen storage. In addition it uses a high efficiency neodymium magnet synchronous traction motor combined with a high performance lithium-ion battery. The lightweight battery provides fast start up, extra power during acceleration, and regenerative braking capabilities. The fuel storage system uses a seamless thin-wall aluminum liner with a carbon-fiber overwrap. Nissan is planning to introduce this vehicle in the 2003 to 2005 timeframe.

6. Projections of Fuel Economy and Cost

6.1 Fuel Economy Projections

Fuel cell vehicles have the potential for significantly better fuel economy than conventional vehicles. This is because fuel cells are more efficient than IC engines, since they operate at a lower temperature and therefore waste less energy as heat. Several factors result in fuel economy penalties, however. These include increased weight due to storage of hydrogen, or, conversely, efficiency losses and increased weight due to on-board reforming. A gasoline reformer fuel cell is much less efficient than a direct hydrogen fuel cell. In addition, fuel cells operate most efficiently within a narrow operating range, thus vehicle hybridization minimizes fuel cell loses during varying load conditions. The main advantage of a hybrid fuel cell vehicle is the ability to use regenerative braking, although some vehicle applications may also need peak power from a battery to assist the fuel cell under heavy load.

Determination of fuel economy for fuel cell vehicles is difficult, as only prototype vehicles have been built to date and few have been tested on driving cycles or against comparable gasoline vehicles. Results from two hydrogen fuel cell prototype vehicles are compared against somewhat comparable gasoline vehicles in Table 5 and 6.

Table 5. Fuel Economy Results for Ford P2000 HFC Vehicle

Vehicle	Weight kg	Efficiency Gasoline Equiv. Liters/100 km		
		Urban	Hwy	Combined
Ford P2000 HFC	1514	4.22	2.92	3.64
Ford P2000 Gasoline	907	N/A	N/A	6.72
Fuel Economy Ratio				1.9

Sources: Peter Schmitz, Ford's Fuel Cell Activities, March 2000, Ford Forschungszentrum Aachen; Ford press releases

Table 6. Fuel Economy Results for DaimlerChrysler NECAR 4

Vehicle	weight kg	Max power kW	kWh/100 km	kg H2/100 km	gasoline L/100km
NECAR 4	1750	70	37	1.07	4.0
A Class Gasoline	1450	60			7.1
Fuel Economy Ratio					1.8

Steam-reformed methanol and autothermal-reformed gasoline fuel cells are currently being tested in the laboratory only. Several academic institutions have developed computer models of fuel cell vehicles to predict fuel economy for these technologies. Their predictions along with the above prototype fuel economy results are shown in Figure 1 for hydrogen fuel cells, Figure 2 for SR methanol fuel cells, and Figure 3 for

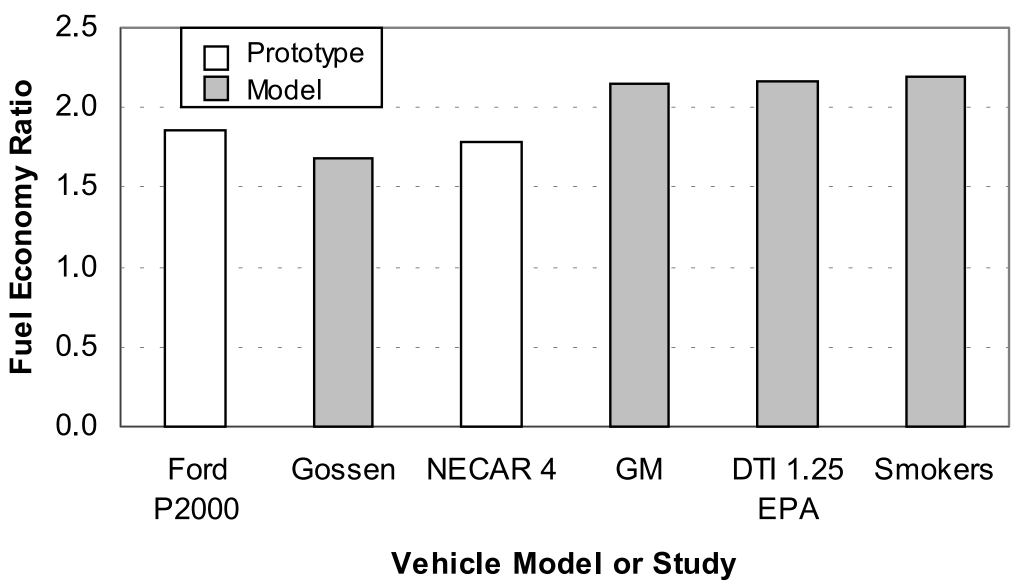

Figure 1. Hydrogen FCV Fuel Economy Comparisons

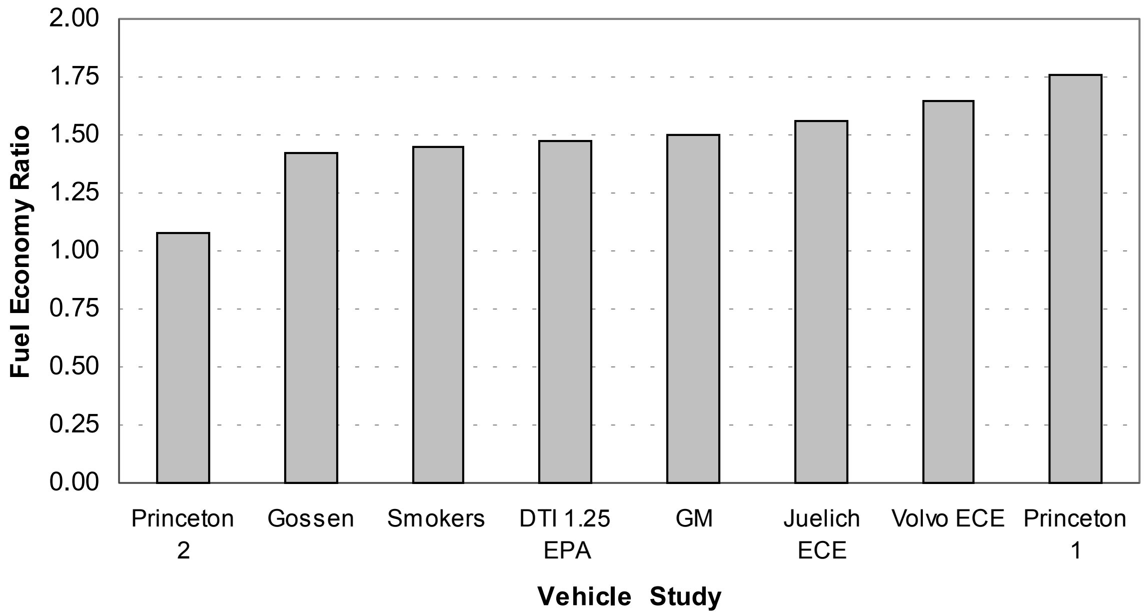

Figure 2. Methanol SR FCV Fuel Economy Comparisons

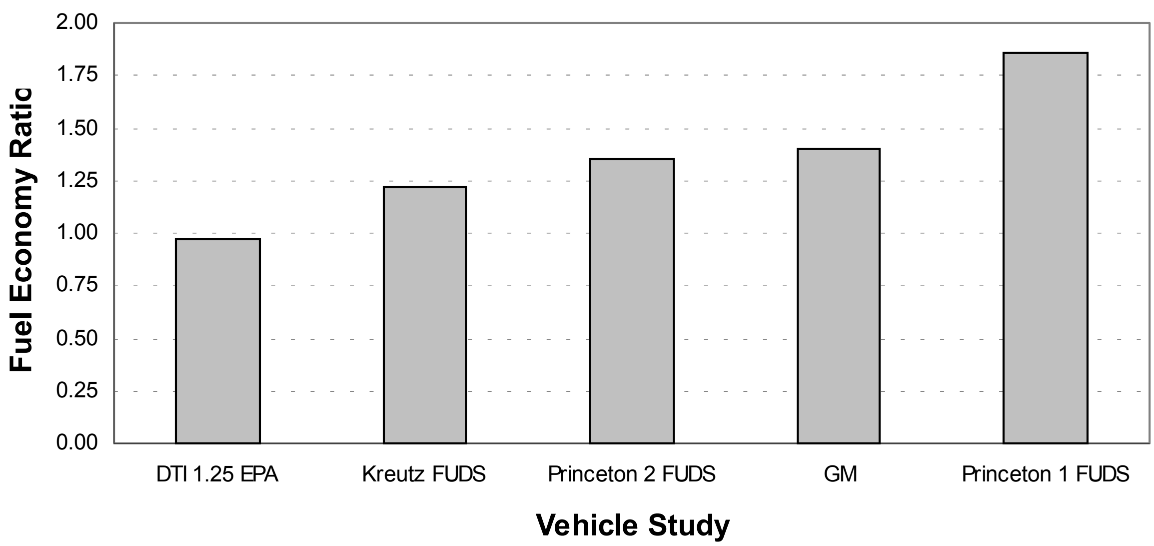

Figure 3. Gasoline ATR FCV Fuel Economy Comparisons

ATR gasoline fuel cells. The fuel economy ratios shown in these figures are the fuel cell vehicle fuel economy converted to miles per gasoline gallon equivalent (mpgge) divided by the fuel economy of an equivalent gasoline IC engine vehicle in miles per gallon. The conventional vehicle would have a fuel economy ratio of 1.0.

By averaging the various study results, fuel economy ratios of 2.0 for hydrogen FCVs, 1.5 for methanol SR FCVs, and 1.4 for gasoline ATR FCVs are calculated. Ethanol ATR fuel cells would likely be about 1 percent more efficient than gasoline ATR FCVs. While these ratios are likely for the near term (2010), DOE Office of Transportation Technologies estimates hydrogen fuel cells to have fuel economy ratios of 3.0 by 2020 and 3.5 by 2040. To reach these levels, significant improvements in fuel cell technology and weight reductions will be needed. Such improvements include those shown in Table 7.

Using Arthur D. Little's fuel cell driving cycle simulation model, fuel economy ratios of 2.5 for direct hydrogen, 1.6 for SR methanol, 1.5 for ATR ethanol or gasoline were found using the assumptions in Table 8. These ratios would be expected for 2010 to 2020 fuel cell vehicles. With an aggressive hybridization strategy, fuel economy ratios of 2.7 for direct hydrogen fuel cell vehicles, 1.8 for methanol SR hybrid fuel cell vehicles, 1.7 for ethanol or gasoline hybrid ATR fuel cell vehicles were calculated. Further improvements in fuel economy would be expected by 2030 due to better fuel cell designs.

It should be noted that these ratios compare future technology fuel cell vehicles with current conventional vehicle technology and that future conventional vehicles will likely have improved fuel economy. In addition, current fuel cell prototype vehicles have somewhat lower performance than conventional vehicles, so projections of fuel economy for fuel cell vehicles could be lower if compared on an equal basis to conventional vehicles.

6.2 Vehicle Cost Projections

Currently fuel cells are in low-volume production and command a high price. Currently PEMFCs cost approximately $500 per kW, which translates into about $25,000 for a 50kW fuel cell engine as compared with about $3,500 for a typical 70kW IC engine. However, Ballard together with experts from Ford and DaimlerChrysler have estimated the cost of the Ballard Mark 900 fuel cell module in large volumes (~300,000 per year) to be about $50 to $60 per kW, perhaps less as volumes increase. This would bring fuel cell costs closer to those for IC engines. Arthur D. Little estimates for Department of Energy indicate current costs of $16,200 for a 50 kW reformer fuel cell. Based upon the improvements listed in Table 7 and the cost reductions listed in Table 8, future costs are estimated to be $7,900 for a 50kW reformer fuel cell and $5,550 for a 50kW hydrogen fuel cell system. This is roughly consistent with Ballard's estimates for the stack. In addition to these costs, a manufacturer mark-up of approximately 74% would be added to these amounts in the final retail price of the vehicle. It is expected that the mark-up on the reformer and fuel cell stack might be reduced as these systems become more reliable and the warranty risk is lessened.

Table 7. Fuel Cell Stack Improvements

Assumptions	Comments
Increase Membrane Operating Temperature from 80°C to 160°C	• Increases CO tolerance – eliminates PrOX and related equipment • Elininates low temperature water economizer and reformate cooler • Assumes reduced stack cooling requirements – fewer coolant plates per cell • Increases radiator LMTD – reduces radiator size
Increased Current Density from 310 to 500 mA/cm^2 at 0.8 V (Reformer System)	• Based on expected improvements in CO tolerance, catalyst utilization and catalytic activity
Improved ATR GHSV from 80,000 to 1,000,000 (Reformer System)	• Assumes short contact time reactior uning 2% wt Rhodium • Decreases fuel processor weight and cost despite high cost of Rhodium
Improved Shift Bed GHSVs significantly (Reformer System)	• Assumes precious metal catalysts and higher allowable exit CO concentration
No sulfur in fuel (Reformer System)	• Assumes energy companies will remove sulfur at the refinery • Eliminates sulfur removal bed
Reduced start-up time from 10 to 5 minutes (Reformer System)	• Assumes shorter start-up times based on smaller fuel processor – less thermal mass to heat up • Reducing start-up times further will require system modifications (e.g. hybrids) • Reduces size of the start-up battery
Increased Current Density from 500 to 750 mA/cm^2 at 0.8 V (Direct hydrogen system)	• Based on experimental data that shows 1.5 times improvement for hydrogen versus reformate fuel cells, and kinetic verification
Increase Total Parasitic Power from 6.1 to 10 kW (Direct hydrogen system)	• Higher hydrogen utilization and smaller anode flows (no inerts) will reduce the expander output power • A detailed analysis has not been performed to date
Decreased Start-up time from t to 1 minute (Direct hydrogen system)	• No warm-up time associated with fuel processor
Decreased Bipolar Plate Material Density from 2.25 to 1.12 g/cm^2	• Based on lighter weight material densities
Decreased Fuel Cell Gasket Perimeter from 1.5 to 1 inches	• Increases cell active area significantly for high power density design points – reduces overall fuel cell stack size
Decreased Weight of Low Temperature Packaging Materials	• Assumes high density plastic materials instead of stainless steel for vessels less than 100°C
Included Ram Air in Radiator Analysis	• Based heat exhange coefficient on GM analysis of an automotive radiator for a fuel cell system that takes RAM air effects into account • Reduces radiator size significantly

Source: Arthur D. Little, “Pathways to Low Cost”, Presentation to DOE, August 2001

Table 8. Fuel Cell Stack Cost Reductions

Assumptions	Comments
Decrease Electrolyte Costs from 100 to 50 $\$/m^2$	• Basic materials are not intrinsically expensive • Assumes high temperature membranes will not be signicantly different in cost and will have equivalent performance
Decrease Platinum Processing Mark-up from 20% to 10%	• Assumes cost reductions at high volumes with future development
Reduced CEM weight and cost from $630 to $500	• Assumes future improvements in CEM design • Reducing costs further will require significant development – the much simpler turbo chargers produced at high production volumes today are about $200/each
Rduced sensor costs	• Reduced high temperature sensor cost from $25 to $10/each • Reduced general sensor cost from $70 to $25/each • Assumes future cost reductions

Source: Arthur D. Little, "Pathways to Low Cost", Presentation to DOE, August 2001

Other costs include the electric motor, motor controller, and a storage battery. Using Arthur D. Little's projections of fuel cell system costs and a cost model developed by Arthur D. Little for the Hybrid Electric Vehicle Working Group to calculate hybrid electric vehicle costs, total incremental vehicle prices above current average mid-size vehicle costs ($18,900) are estimated to be about $9,300 higher for a direct hydrogen mid-size FCV, $10,000 for a SR methanol mid-size FCV and around $11,200 higher for a gasoline or ethanol autothermal reformer-based mid-size FCV in the near-term (2010 to 2020). For aggressive hybridization strategies, incremental costs of $9,000 for a direct hydrogen FCV, $9,700 for a SR methanol FCV and $10,400 for a autothermal reformer gasoline or ethanol FCV are calculated. Detailed results are shown in the Appendix.

Further cost reductions are possible as fuel cells become more reliable and warranty issues are less of a concern to automobile manufacturers. Additional savings could occur from larger production volumes through the learning curve phenomena.

7. Market Barriers and Drivers

There are several barriers to the introduction of fuel cells, at least in the near term. The present cost of fuel cell vehicles and the lack of a hydrogen fueling infrastructure are probably the largest near-term barriers.

As discussed in Section 6.2, significant price differentials exist between fuel cell vehicles and their conventional counterparts, at least in the near and mid term. If price competitiveness with IC engine vehicles can ever be reached, this barrier would be eliminated. However, in the near term, incentive programs and market drivers might help overcome the resistance to the initial high vehicle price, but significant subsidies will be needed to obtain more than a limited market penetration. ARB is giving multiple credits for direct hydrogen fuel cell vehicles in their partial ZEV credit program. For hydrogen fuel cell vehicles produced through 2002, one hydrogen fuel cell vehicle is equal to 40 pure electric vehicles in meeting the ARB ZEV mandate. Between 2003 and 2005, hydrogen fuel cell vehicles are worth 12.5 pure EVs phasing down to 3.5 in 2012. This sort of incentive can help manufacturers offset the potential costs of building EVs.

The capital costs of hydrogen stations are not fully known at this time and will depend on whether a liquefied hydrogen or compressed hydrogen will be stored and/or produced at the station. Costly fire and safety requirements are likely to be the norm at hydrogen stations in the early years of deployment. It is reasonable to assume that the cost of hydrogen stations for automotive applications are likely exceed the current cost of a large CNG station (i.e., as much as $1 million), at least in the early developmental years. In fact, hydrogen stations currently being built in California have costed considerably more.

The other main barriers to hydrogen fuel cells include on-vehicle storage issues, and consumer acceptance of alternative fuel refueling requirements. On-vehicle storage issues also present barriers to commercialization. Current-technology storage systems for vehicles have significant weight and/or volume penalties and provide only limited vehicle range. Compressed hydrogen needs to be pressurized to at least 34 MPa in order to have reasonable range, while liquefied hydrogen needs cryogenic storage and has refueling and storage losses. While metal hydrides reduce safety concerns, the energy storage weight is very large. Hydrogen storage problems such as these need to be overcome before direct hydrogen fuel cell vehicles will be viable.

While it is possible to use autothermal reformers and on-board storage of gasoline for fuel cell vehicles, efficiency losses in the reformer reduce the fuel economy and emissions benefits of fuel cells. Further work is needed to improve reformer efficiency and minimize emissions.

Finally, some experts believe that wide-scale consumer acceptance of gaseous fuels in passenger cars is a long way off. Special fueling equipment and handling are needed as well as codes and regulations for fueling stations, on-board vehicle storage, and vehicle garaging. These issues need to be resolved before full scale commercialization of direct hydrogen fuel cell vehicles can be achieved.

Market drivers include criteria air pollution, greenhouse gas reductions, energy security, the possibility of using the electric drivetrain as an auxilary APU, and reduced noise. Criteria air pollution reductions are a large driver since fuel cells can be built to be zero emission vehicles. Fuel cells also have a distinct advantage in well-to-wheels efficiency and emissions, directly reducing greenhouse gas emissions. While conventional use of petroleum fuels in IC engines is likely to be the predominant means of vehicle propulsion for at least the next two decades, price increases and eventual shortages in gasoline and diesel could drive consumers to consider fuel cell vehicles, particularly those that provide flexible fueling options.

8. Market Penetration

Because fuel cell technology is still in an early stage of development, estimates of market share over time are fraught with uncertainty. First, technology performance and cost uncertainty for fuel cells is considerably greater than that for other technologies. Second, planned environmental regulation is expected to have a major impact on the level of acceptance of fuel cell technology. Third, the fact that fuel cells would represent the most radical shift in powertrain technology makes it more difficult to anticipate customer and industry response to fuel cells.

Because technology plays such an important role, we have developed three different technology development scenarios to understand the dynamics controlling the future role of fuel cells. The focus of the scenarios is on the 2010 timeframe because it is unlikely that commercial FCVs will be developed much before then; if it does not happen by then, the required level of support is not likely to continue, based on our current understanding of industry dynamics. The assumptions underlying the three scenarios are summarized as follows.

- *Demonstration-Only/Fleet Markets Scenario.* In this scenario fuel cell technology demonstrations will not lead to a viable technology for (light duty vehicle) applications and the current level of R&D spending will not continue beyond 2005. Niche applications in local fleet vehicle markets (e.g., buses) will occur and create value for fuel cell producers, but markets for FCVs will not approach significant levels for LDV markets. Thousands of vehicles will be sold in 2010, but no significant growth will occur after that.

- *Niche Market Scenario.* In the regulated scenario, fuel cell technology will be sufficiently developed to provide solutions for small LDV markets, most notably markets driven by strict environmental regulations. This means that weight and cost will be reduced by 2008 to make FCVs superior to battery-electric vehicles and thus, in those regulated markets, fuel cell powertrains will capture increasingly large fractions of the market, until they eventually dominate those markets and facilitate such regulation. Hundreds of thousands of LDVs will be sold, although fuel cell powertrain costs will hover around $100/kW. This technology scenario is consistent with the future technology scenario described above.

- *Technology Victory Scenario*. In the technology victory scenario, fuel cell technology will achieve cost and performance levels that make it broadly competitive with conventional powertrain technologies. This would require significant additional improvement in technology principally to achieve a cost approaching $50/kW for the fuel cell powertrain. Additional technology breakthroughs will be required; we do not expect these to come to fruition until well after 2010. In the meantime, the projections for this scenario would mimic the Regulated Scenario. Transition from the demonstration-only scenario would appear to be unlikely, because the development time and expenses required could probably not be supported without significant intermediate sales.

We have developed market forecasts based on these scenarios, assuming expected scenarios with respect to oil prices and environmental factors. The results for the niche market and technology victory scenarios are shown in Figure 4. The figure shows that fuel cell market projections for the 2008–2020 timeframe currently range from marginal impact to noticeable impact. Even so, the most significant impact is not expected to happen until the following decade. For the demonstration-only scenarios, FCV production is not expected to exceed 1000 vehicles per year. Technology victory assumes cost competitiveness with conventional drivetrains.

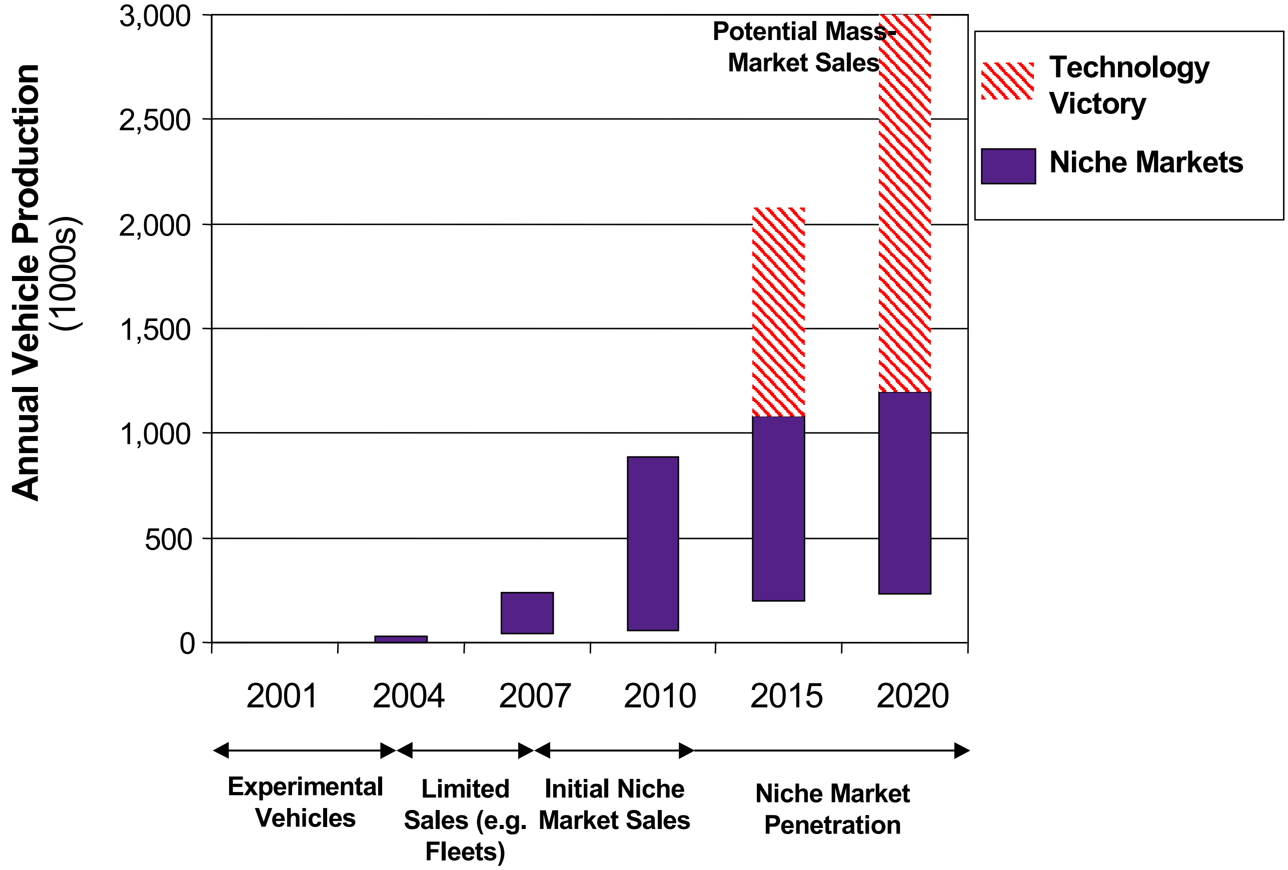

Figure 4. Global Market Projections for Fuel Cell Vehicles

Compared with most projections made by other industry players over the years, our projections are more conservative. Others have projected that a 35 million–vehicle market will develop by 2020, with sales hitting one million as early as 2007, but we believe that it will take time to improve the performance of fuel cell power units, to optimize their integration with the vehicles, and to develop true commercial vehicles based on them. If hydrogen is used as a fuel, the timeframe for this development may be shorter, but the establishment of a hydrogen infrastructure with sufficient coverage for light-duty mass markets will likely become a limiting factor in vehicle sales growth.

9. Conclusions

Fuel cell vehicles promise increased fuel economy and zero emissions. Unlike battery vehicles, refueling is quick and the range can potentially be similar to conventional vehicles. Direct hydrogen stored on-board the vehicle is the most promising fueling option from the standpoint of efficiency and emissions, but presents significant storage problems and may pose safety issues. Reformers allow use of conventional liquid fuels, which are converted to hydrogen, but at a fuel economy penalty and additional system cost and complexity.

Direct hydrogen fuel cell vehicles can provide fuel economies that are 2 to 3 times better than current conventional IC engine gasoline vehicles. Fuel cell vehicle cost is still an issue, but with additional technology breakthroughs and at high production levels it is estimated that they could approach the low costs of current IC engine vehicles. In addition, the cost of IC engine vehicles will likely increase as they are required to meet progressively lower emissions standards and better fuel economy requirements. In addition, only fuel cell and battery electric vehicles can claim zero emissions.

While barriers exist to introduction of a hydrogen infrastructure, reformer fuel cell vehicles can bridge the gap while a hydrogen fueling infrastructure is built. The proliferation of fuel cell vehicles is highly dependent on achieving cost and performance parity with conventional vehicles and consumer acceptance of fueling with a gaseous fuel.

Serious challenges in technology performance, weight reduction, and cost still must be overcome. If this is achieved, and economic and regulatory environment are favorable, fuel cells could have a significant impact as the future propulsion power source for LDVs, and the impact would be long-term. FCV market share is not expected to rise above 1% until after 2010, and market shares above 10% worldwide would not likely occur before 2020, even if technology development is successful. Finally, fuel cells could have considerable impact in light duty vehicle markets (and heavy duty and special purpose vehicle markets as well) as APUs.

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APPENDIX

Table A-1. Fuel Cell Vehicle Costs (Mid Term)

Vehicle Type	Gasoline Baseline	Hydrogen PEM	Methanol SR PEM	Ethanol	Gasoline ATR PEM
Engine/Fuel Cell Power (kW)	107.0	58.1	62.2	62.5	61.5
Battery Net Power (kW)		9.0	9.0	9.0	9.0
Motor Power (kW)	107.0	67.1	71.2	71.5	70.5
Glider ($)	$13,000	$13,000	$13,000	$13,000	$13,000
Engine/Fuel Cell ($)	$3,130	$5,480	$8,390	$9,020	$8,900
Transmission/Controls/Accessories ($)	$2,260	$5,280	$5,460	$5,480	$5,430
Energy Storage ($)	$70	$2,950	$880	$870	$860
Precious Metals ($)	$440	$1,460	$1,120	$1,840	$1,810
Vehicle Retail Price ($)	$18,900	$28,170	$28,850	$30,210	$30,000
Incremental Price ($)		$9,270	$9,950	$11,310	$11,100
Fuel Economy (mpgge)	30.6	76.2	49.0	45.6	45.5
Fuel Economy Ratio		2.5	1.6	1.5	1.5

Sources: Arthur D. Little projections of fuel cell costs for DOE and hybrid electric vehicle costs for EPRI

Table A-2. Fuel Cell Vehicle Costs with Aggressive Hybridization (Mid Term)

Vehicle Type	Gasoline Baseline	Hydrogen PEM	Methanol SR PEM	Ethanol	Gasoline ATR PEM
Engine/Fuel Cell Power (kW)	107.0	37.2	37.4	37.4	37.3
Battery Net Power (kW)		29.3	32.4	32.3	31.4
Motor Power (kW)	107.0	66.5	69.8	69.7	68.7
Glider ($)	$13,000	$13,000	$13,000	$13,000	$13,000
Engine/Fuel Cell ($)	$3,130	$4,240	$6,850	$7,230	$7,090
Transmission/Controls/Accessories ($)	$2,260	$5,250	$5,400	$5,400	$5,350
Energy Storage ($)	$70	$4,450	$2,690	$2,690	$2,650
Precious Metals ($)	$440	$930	$670	$1,100	$1,100
Vehicle Retail Price ($)	$18,900	$27,870	$28,610	$29,420	$29,190
Incremental Price ($)		$8,970	$9,710	$10,520	$10,290
Fuel Economy (mpgge)	30.6	83.8	55.5	53.4	52.2
Fuel Economy Ratio		2.7	1.8	1.7	1.7

Sources: Arthur D. Little projections of fuel cell costs for DOE and hybrid electric vehicle costs for EPRI